Interpreting lab creep experiments: from single contacts … … to interseismic fault models

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Motivation

- Can we use lab experiments to constrain large-scale fault models? what are the limitations?

- What is the best way to infer microphysical processes from macroscopic measurements?

- How can we account for observational errors, model uncertainties, and potential deformation regime changes during each experiment?

Our Bayesian inference scheme

Observations

Experimental or simulated porosity time series

Choice of the model m *

When the grain-size effects can be neglected, and we make no assumption on the mechanisms, we can choose a creep law of the type:

$$\frac{\partial \varphi}{\partial t} = \theta_0 \times \sigma_{\mathrm{eff}}^{\theta_1} \times \exp(-\theta_2/(RT)) \times \exp(\theta_3 \varphi)$$

Stress exponent

Apparent activation energy

Prerequisite

- Integration of the creep law: we want to use the data, not a subproduct of it

- Reparametrization such that the problem is as linear as possible (work with Gaussians)

The five steps of the inference

A: Choose the parametrization making the problem as linear as possible

B: When a factorization appears in the new Bayesian network, adopt a hierarchical inference scheme

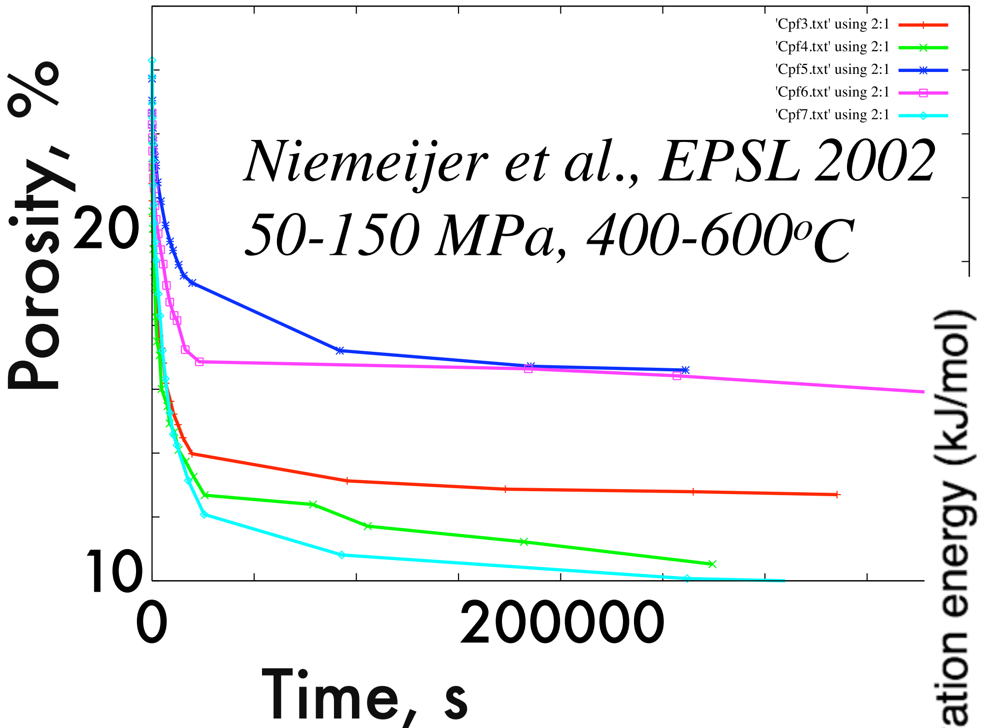
C: Calculate the joint probability density function according to the graph structure (the joint pdf is proportional to the posterior pdf).

D: Eliminate the nuisance parameters (marginalization step)

E: Revert from the new parametrization to the original parameters θ_i *

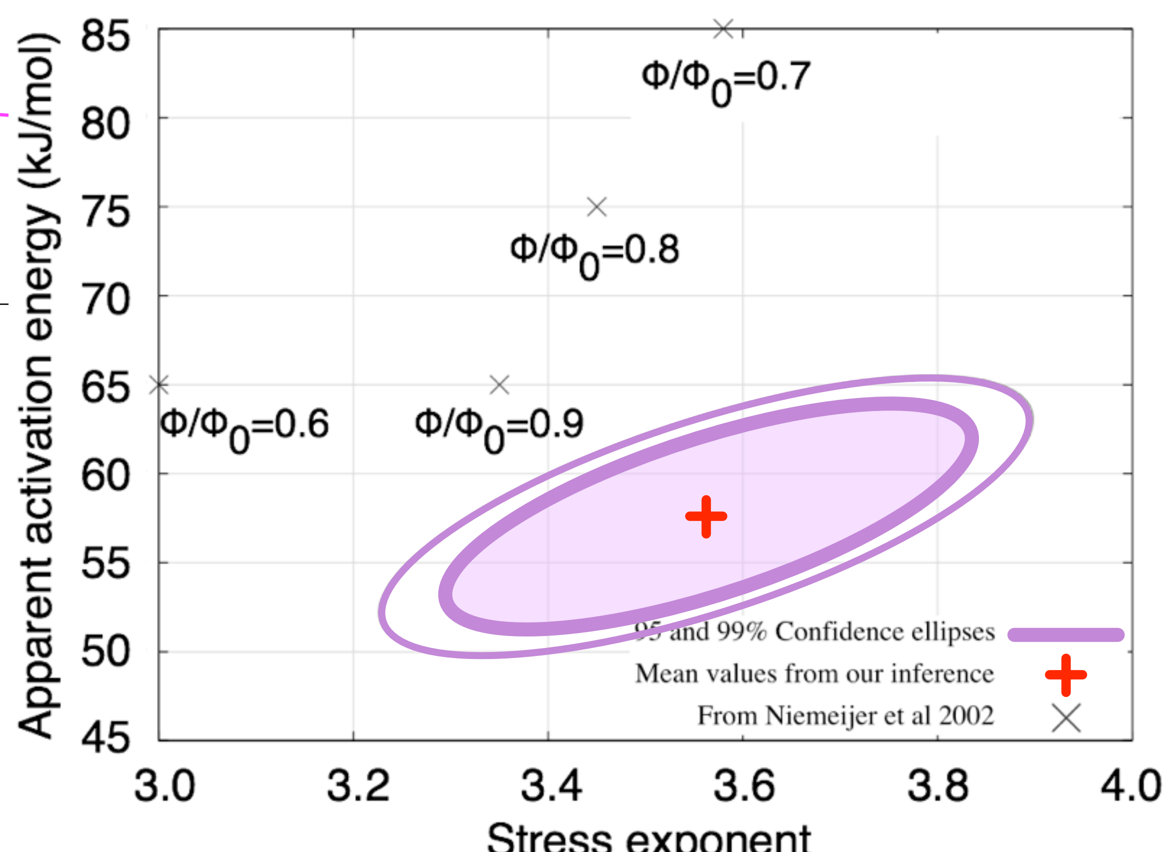
Fitzenz & al., MaxEnt 05

Application to real experimental creep data



Subset $\Phi/\Phi0 \in [0.5,0.8]$: 53 points

θ_j={4.2 10^{-13}; 3.56; 57.6 kJ/mol; 0.71}, with std. dev. of 2.3 10^{-13}, 0.11, 2.6 kJ/mol, and 0.016 resp.



Fitzenz & al., JGR 07

Interpretation and questioning

Stress exponent 3.5
Apparent activation energy 60 kJ/mol

Most likely mechanisms :
compaction rate-controlled by dissolution
+ cataclasis or stress corrosion

However:
The relation between contact stress and applied stress may be affected by changes in grain packing

We need to perform a test on a more controlled system: could we identify pure pressure solution?

Validation procedure:
simulated pressure solution

Single contact model by Bernabe and Evans 2007 based on the evolution of the contact shape

- Stress exponent 1
- Apparent activation energy:
  between 72 kJ/mol (contact dissolution)
  and 15 kJ/mol (interface diffusion)

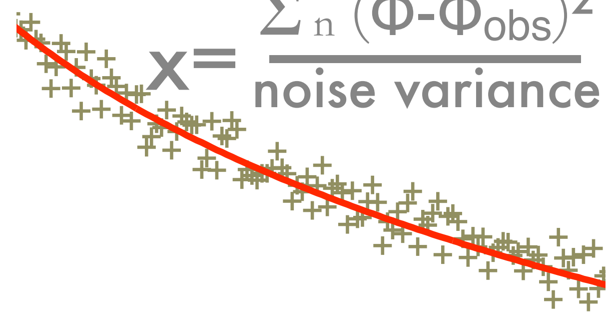
throughout the simulated experiments

Data transformed into porosity time series by assuming a simple cubic packing geometry + Gaussian noise

Challenge:
Analyze data whose behavior is driven by the contact area without knowing how contact area evolves through time

Identifying transitions

For each experiment, we estimate the maximum number of points n belonging to the same deformation regime using a χ^2 test

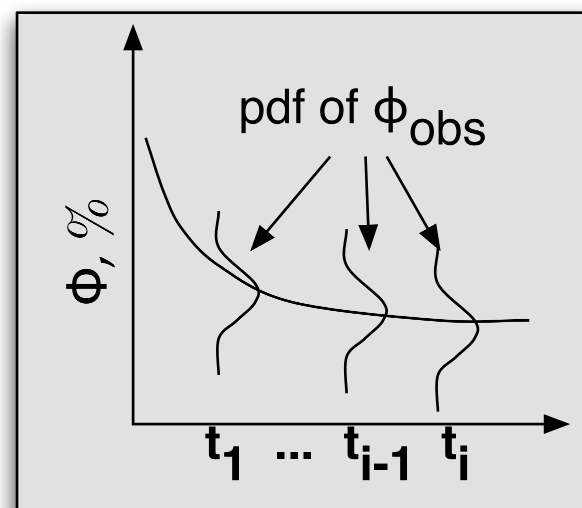


$$x = \frac{\Sigma_n (\Phi-\Phi_{obs})^2}{\text{noise variance}}$$

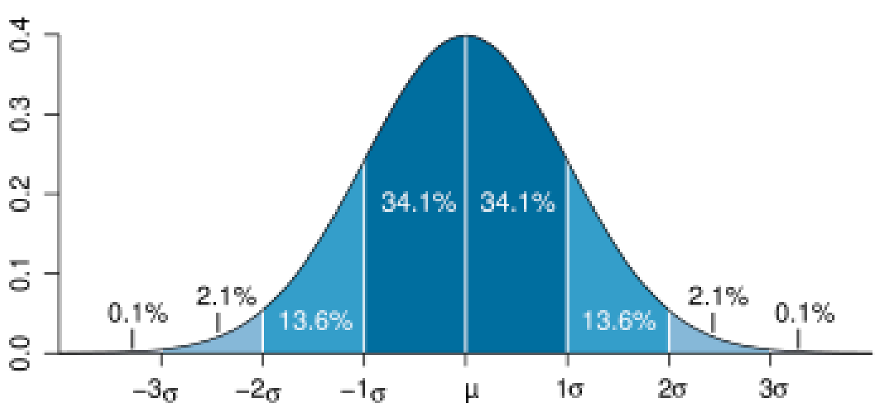
x = realization of a random variable

hypothesis testing: x is normally distributed, variance σ^2, mean μ

$|x-\mu|>2\sigma$: less than 5% likely to have occurred by chance



with $\Phi(t)=m(T,\sigma_{eff},\theta,\varphi_0,t)$



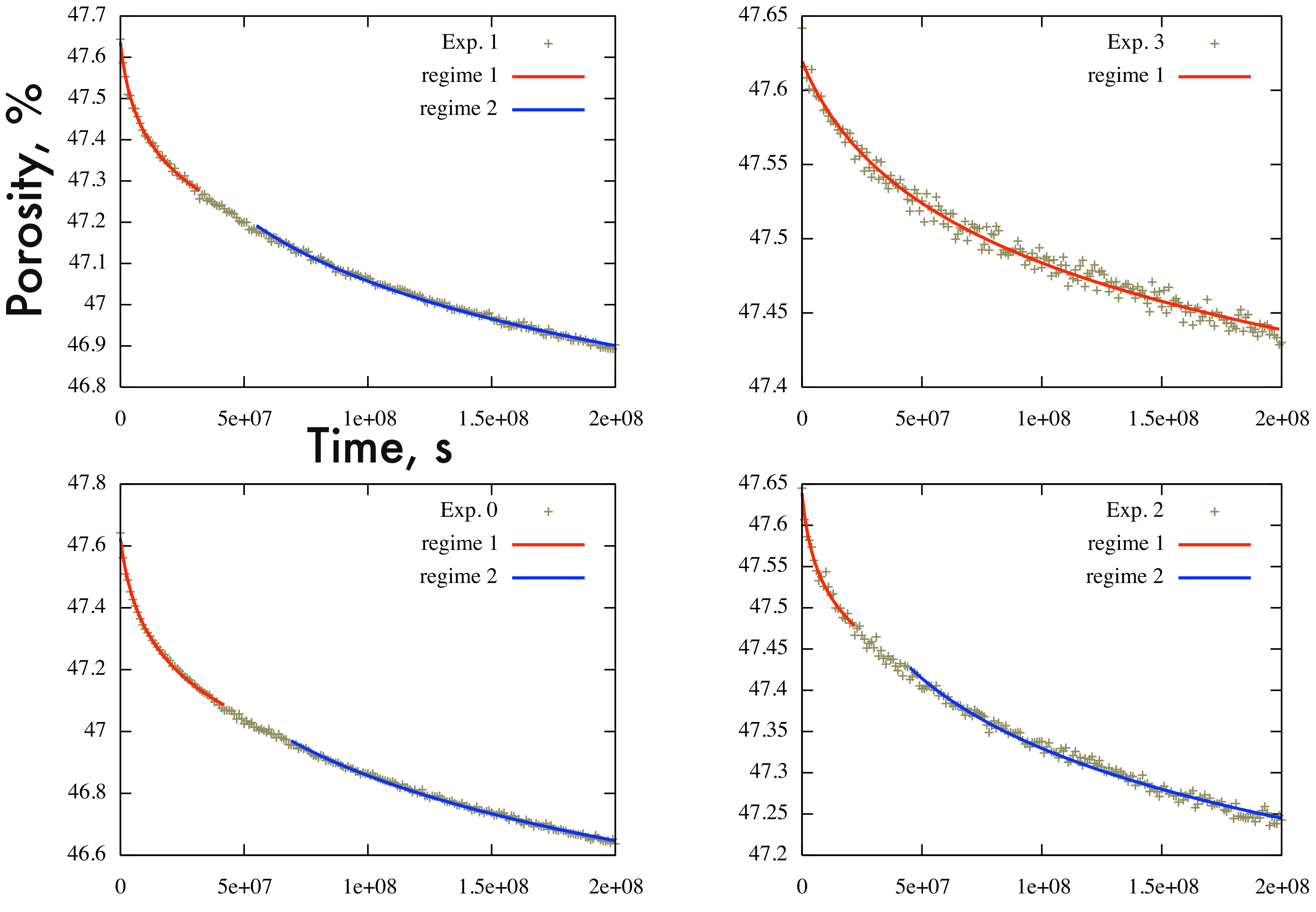
10 simulated experiments

Exp #	σ_n (MPa)	T (K)
0	5.482	508
1	2.564	508
2	0.495	508
3	0.080	508
4	$1.591\ 10^{-2}$	508
5	0.495	574
6	0.495	542
7	0.495	508
8	0.495	472
9	0.495	435

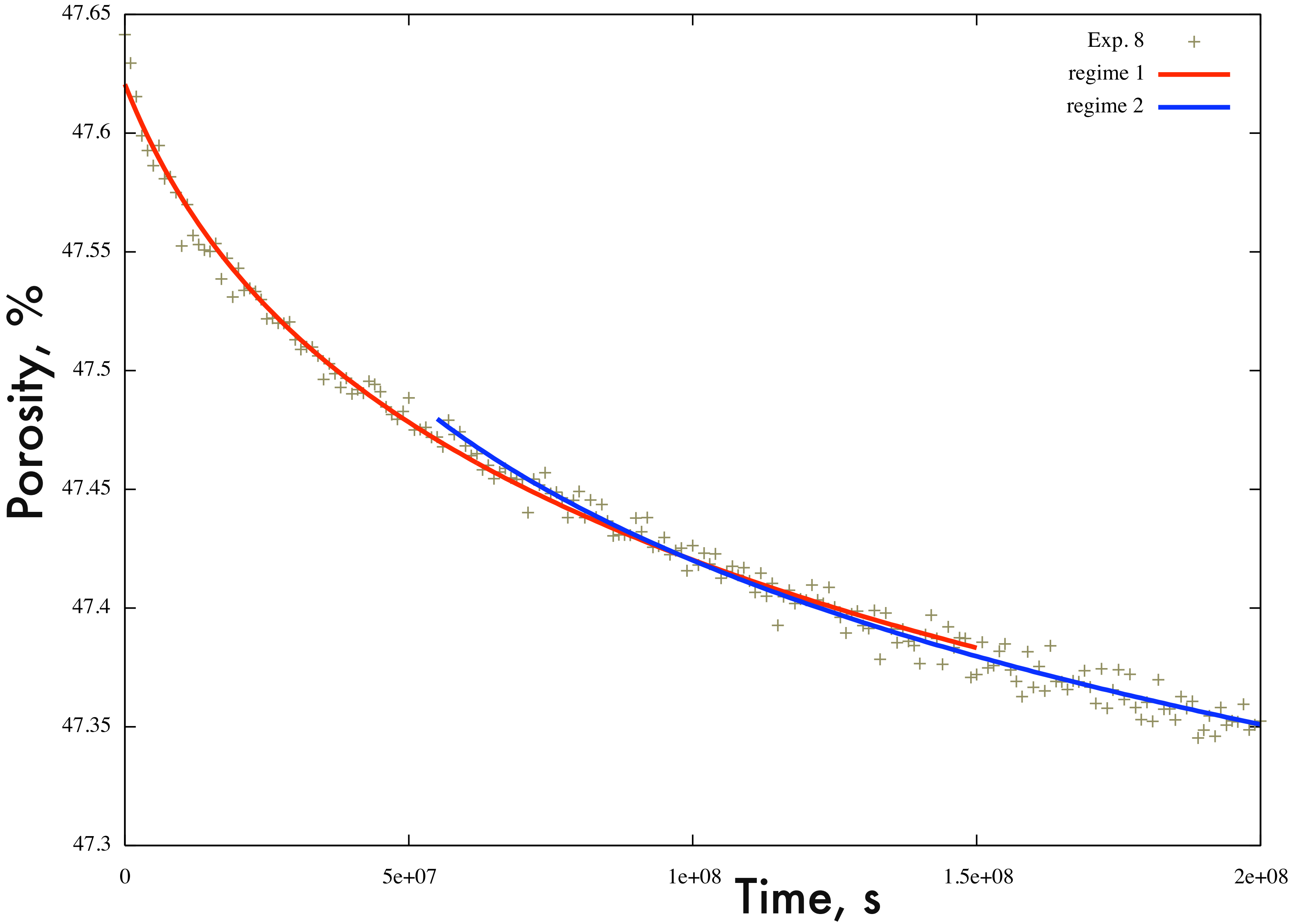
After Bernabe & Evans 2007

201 points/experiment,
Gaussian noise with std dev 0.005

Identifying transitions



Identifying transitions



The 2 deformation regimes (at 3σ)

Regime 1:	Stress exponent 0.97 +/- 4.4 e-3 Apparent act. energy 56.9 kJ/mol +/- 0.3 kJ/mol
Regime 2:	Stress exponent 1.2 +/- 5.4 e-3 Apparent act. energy 32.8 kJ/mol +/- 0.1 kJ/mol

- Stress exponents close to 1 as assumed in Bernabe & Evans
- Both activation energies between 72 kJ/mol (contact dissolution) and 15 kJ/mol (interface diffusion);
- For the early stage, Bernabe & Evans obtained 58 kJ/mol with a different method (knowing the contact area as a function of time);
- The late times are better approached with our method.

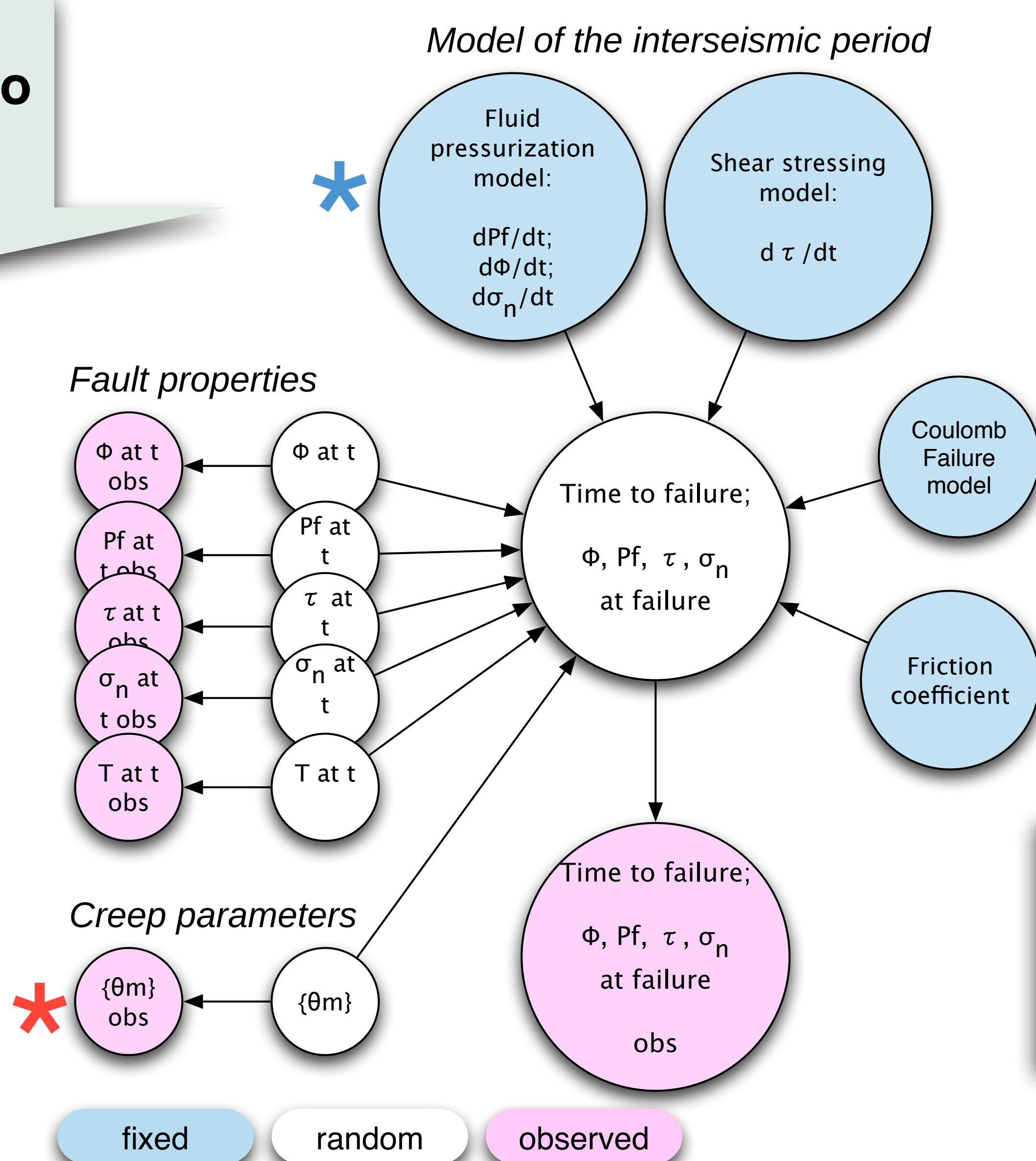
Validation procedure:
simulated pressure solution

Conclusion:

- With stress exponents close to 1 and a decreasing apparent activation energy from above 57 kJ/mol down to below 33 kJ/mol, we can infer that the deformation is pressure solution, mostly controlled by dissolution at the beginning, and with a larger contribution of interface diffusion as contacts grow.
- The times (and porosities) of the transition are T- and σ_n-dependent.

Time to failure using the creep law inferred using the Niemeijer et al. data

Monte Carlo sampling through

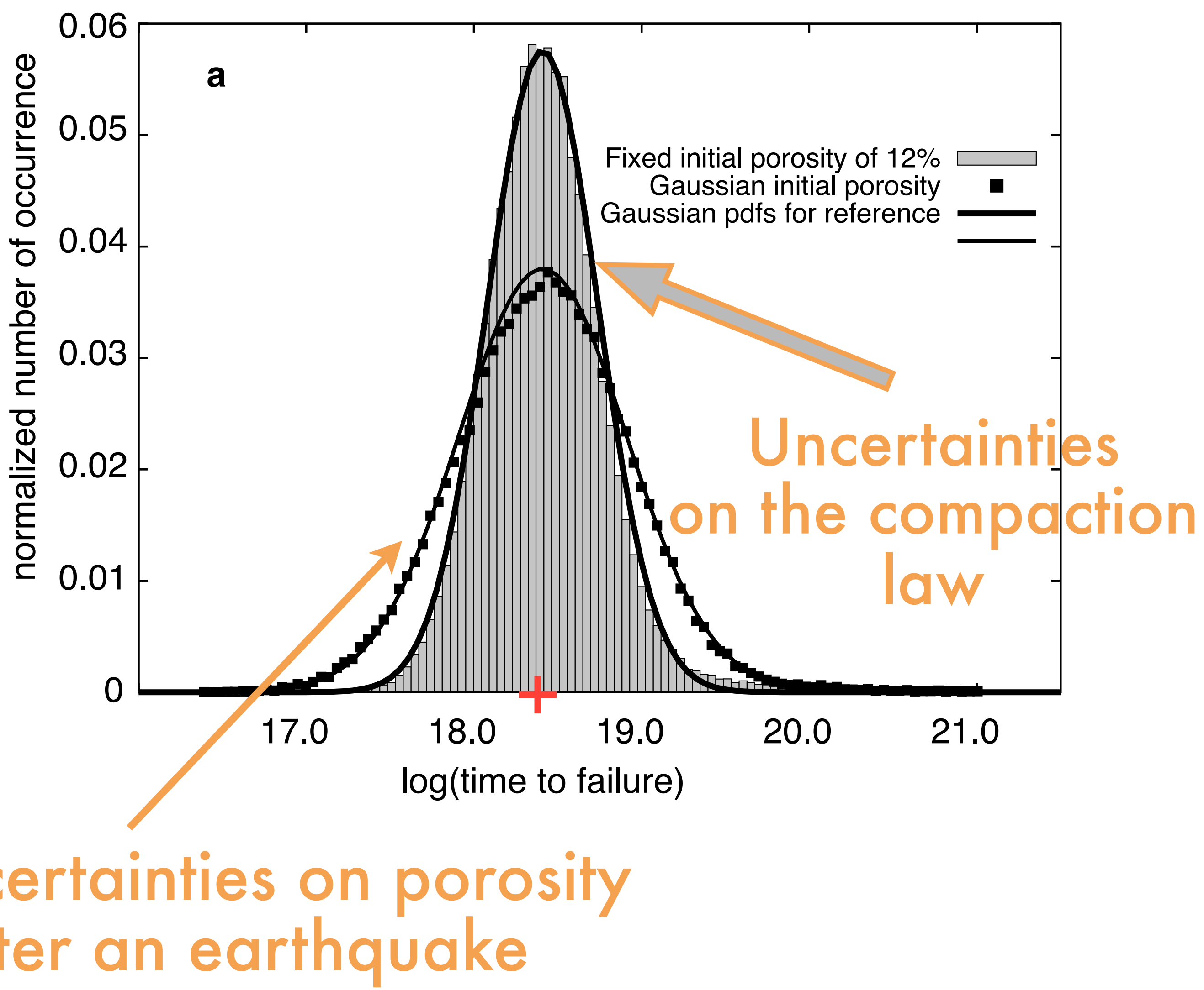


Results in terms of time to failure

Time to failure distributions

- undrained
- 1 fault element
- t=0, 12% porosity
- z=3km
- {θj} from previous inversion
- (static) friction=0.6
- $d\tau/dt$=2.5 bar/year
- $d\sigma_n/dt$=0
- Coulomb failure:

  $\tau \geq friction*(\sigma_n - P_f)$



Conclusions

1. We developed a Bayesian inference scheme that we validated using simulated pressure solution experiments;

2. The analysis of simulated experiments can also guide the design of future experiments;

3. We applied this method to real compaction data obtained at hydrothermal conditions;

4. We showed how to propagate the uncertainties to time to failure distribution;

and future directions

This type of Bayesian framework seems promising for future efforts to compute earthquake probability models including the "known" fundamental physics, different types of data, their observational errors, and the model uncertainties when they exist.